Discovering Asymmetric Dark Matter with Anti-neutrinos

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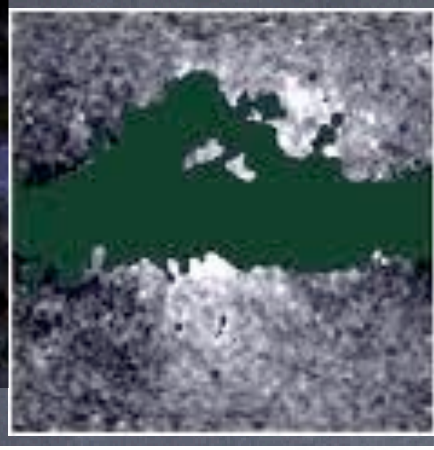
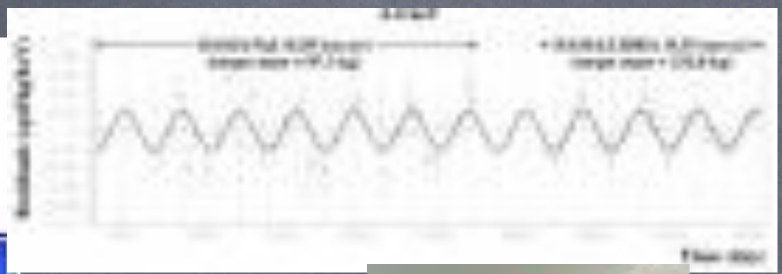
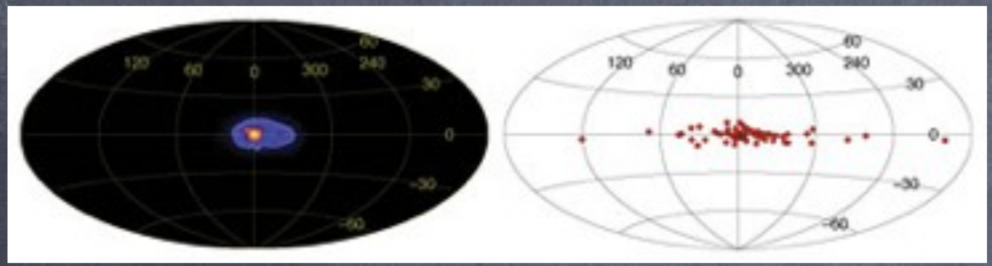
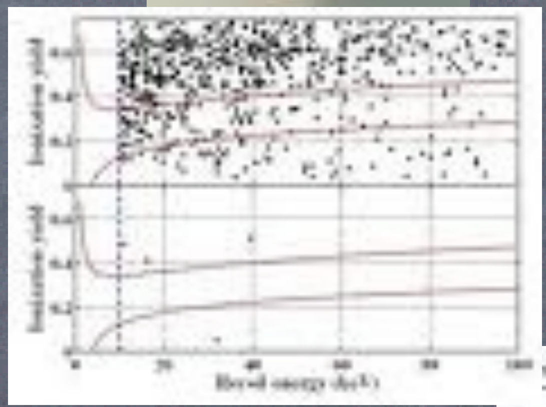
arXiv: 1003.5662:
B. Feldstein, ALF

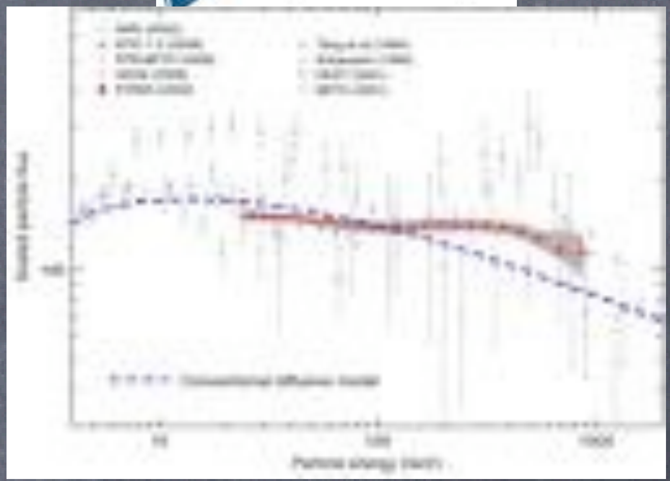
Dark Matter Searches

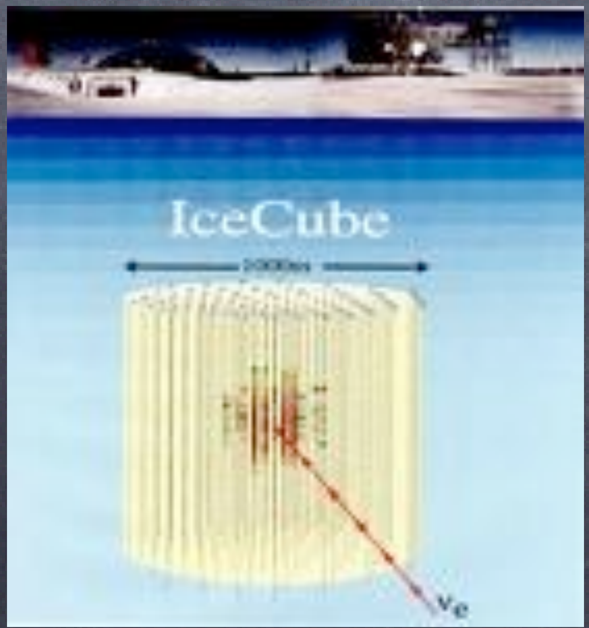


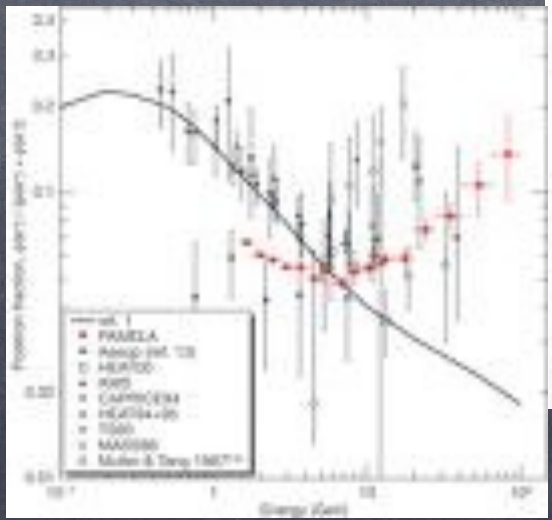




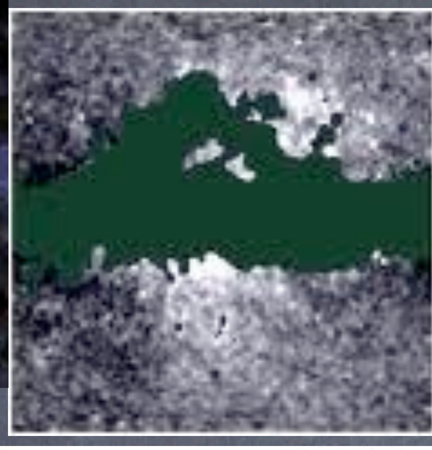


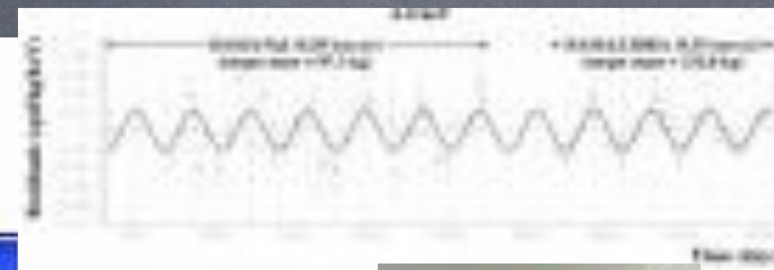




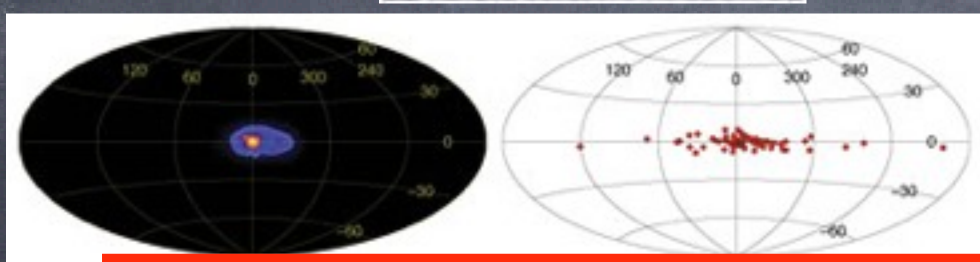
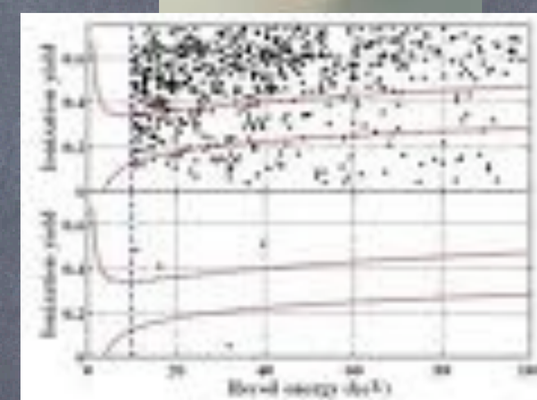
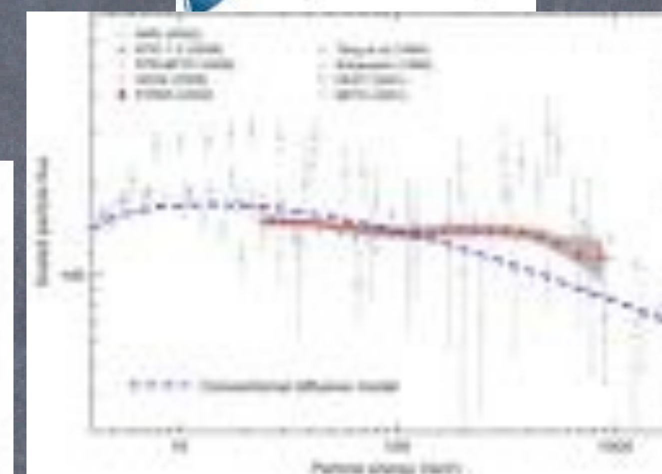


Dark Matter Searches

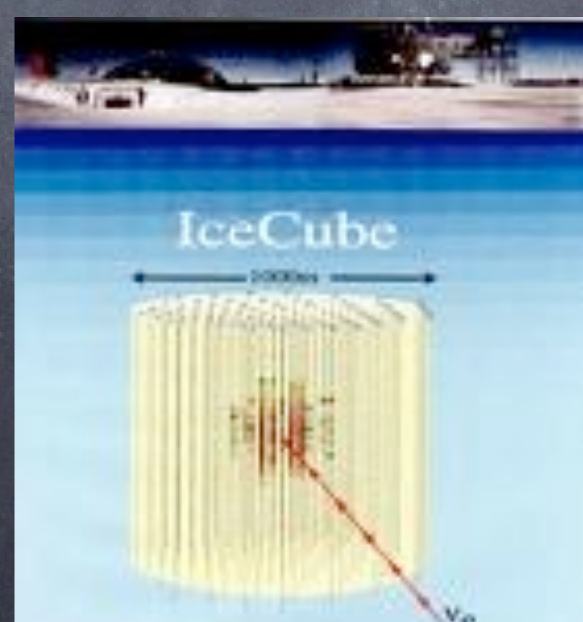



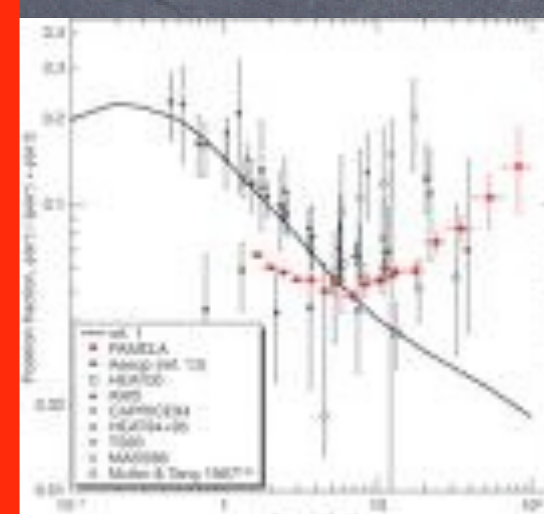



Fermi
Gamma-ray Space Telescope

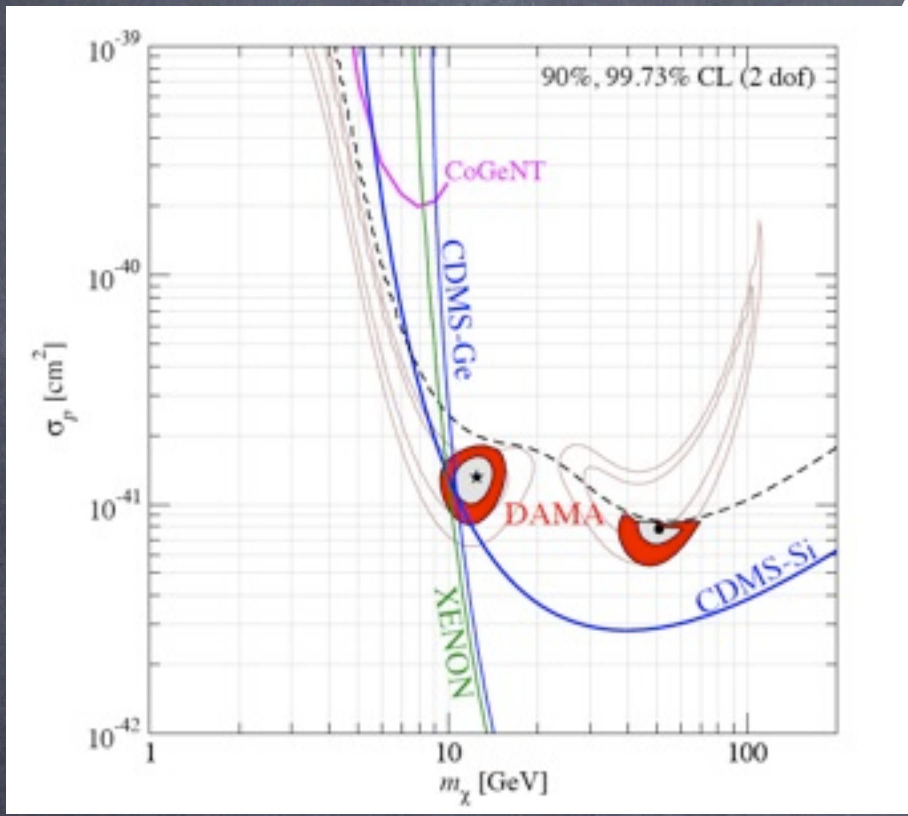
Neutrinos

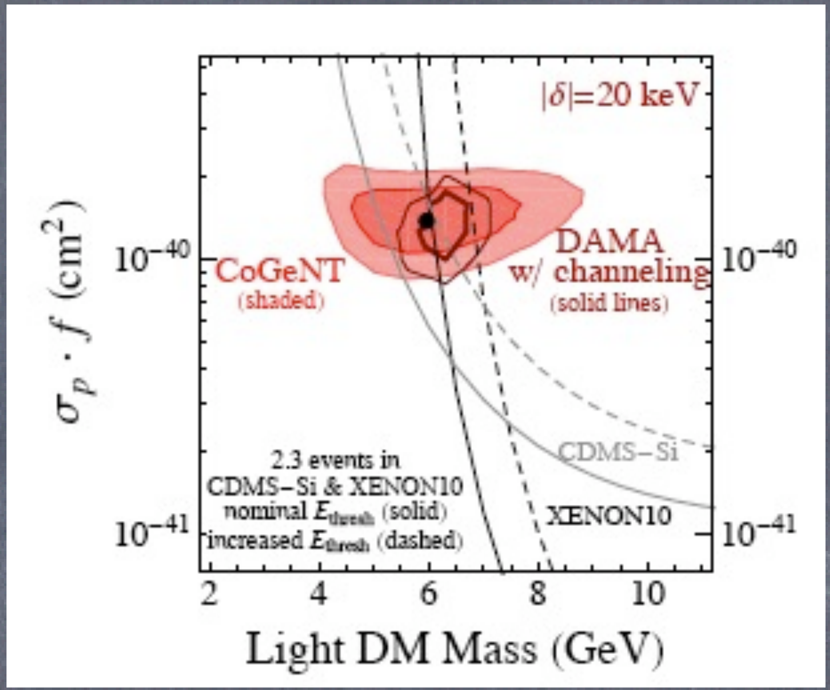



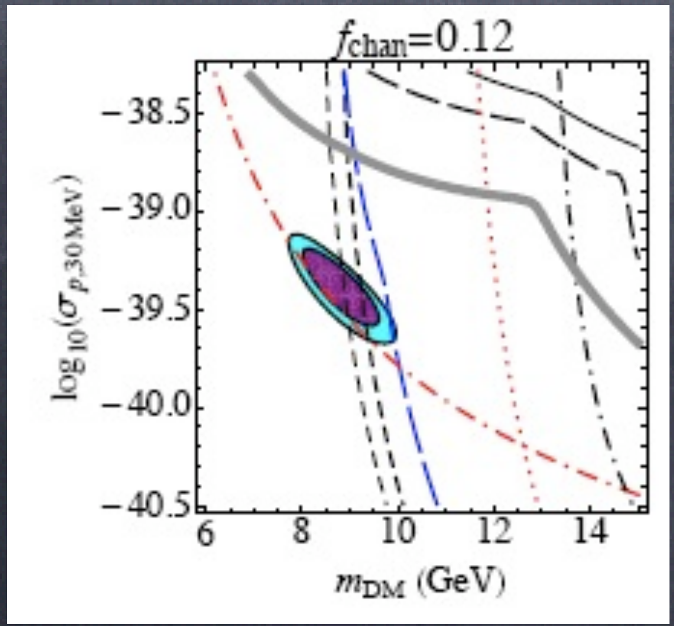


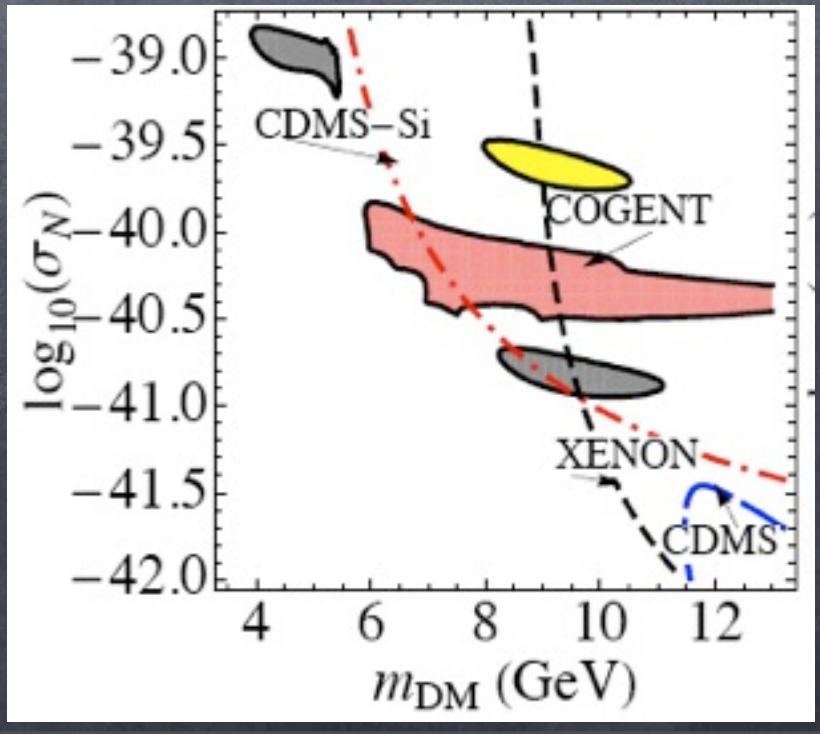

Direct Detection

DAMA, CoGeNT







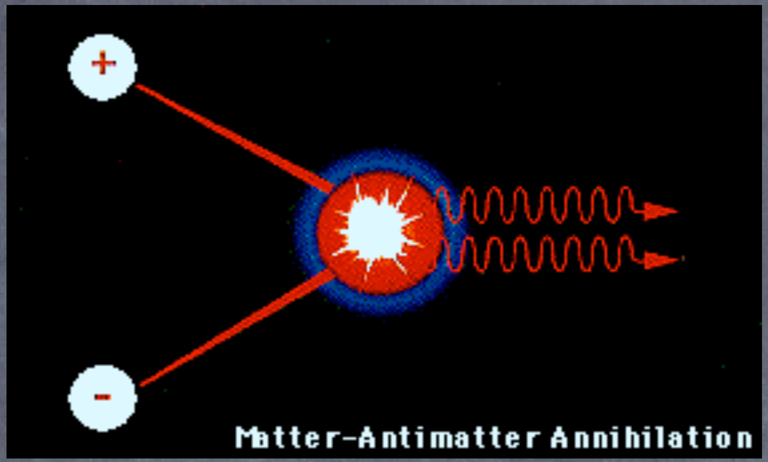


Outline

- Asymmetric Dark Matter and asymmetry x-fer
- Neutrino signal
- General models and some model-building issues
- Annihilations

Relic Density

- Favorite story: annihilation freeze-out



- Alternative: asymmetry

Asymmetric DM

- Similar to Baryons:

$n_B > \bar{n}_B$

B asym generated

Low T: B conserved

Left with $n_B - \bar{n}_B$

T

- DM: $n_X > \bar{n}_X$

Linked asymmetry

- Appealing idea: Link SM baryon asymmetry to DM asymmetry
  (Barr,Chivukula,Farhi; D.B. Kaplan;etc.)
- Various mechanisms in literature, focus on: asym transfered through chemical equilibrium at high temperatures

$$\Delta\mathcal{L} = \frac{\mathcal{O}_{\rm DS}\mathcal{O}_{\rm SM}}{\Lambda^{d-4}}$$

(D.E.Kaplan, Luty, Zurek)

- $\mathcal{O}_{\rm DS}, \mathcal{O}_{\rm SM}$ gauge-invariant, baryon/lepton # carrying
- e.g. $\mathcal{O}_{\rm SM} = HL, LLE^c, (HL)^2,$ etc.;

$$\Delta\mathcal{L} = \frac{X(HL)^2}{\Lambda^2}$$

Transfer of Asymmetry

- High temp: DS ⟷ SM interaction in equilibrium
- Convenient to work w/ chemical potential

$$n = \frac{1}{(2\pi)^3}\int \frac{d^3p}{e^{-(E-\mu)/T} \mp 1}, \qquad \bar{\mu} = -\mu$$

$$n - \bar{n} = \begin{array}{ll} \frac{\mu T^2}{6} & \text{fermions} \\ \frac{\mu T^2}{3} & \text{bosons} \end{array}$$

$$X(HL)^2 \Rightarrow \mu_X = -2(\mu_H + \mu_l)$$

Harvey, Turner, (std analysis)

SM interactions-> relations among $\mu_H, \mu_l, \mu_e, \mu_u, \ldots$

Relation to symmetries

No sym: lots of interactions,
lots of constraints

e.g.

$$\begin{array}{ccc} XY & & \mu_X + \mu_Y = 0 \\ XYY & & \mu_X + 2\mu_Y = 0 \\ XXY & \Rightarrow & 2\mu_X + \mu_Y = 0 \\ \ldots & & \ldots \end{array}$$

$$\mu_X, \mu_Y \longrightarrow 0$$

- But, with a conserved charge,

$$\Delta\mathcal{L} = \psi_1\psi_2\ldots\psi_n \qquad \sum_i^n q_i = 0$$

Non-trivial solution: $\mu_i = cq_i$

c free, set by init. conditions

DM abundance

$$\Delta\mathcal{L} = \frac{X(LH)^2}{\Lambda^2}$$

$$U(1)_{\rm B-L}, U(1)_Y \qquad \mu_H = \frac{1}{2}C_Y, \mu_l = -\frac{1}{2}C_Y - C_{\rm B-L}, \mu_e = -C_Y - C_{\rm B-L},$$

$$\mu_q = \frac{1}{6}C_Y + \frac{1}{3}C_{\rm B-L}, \mu_u = \frac{2}{3}C_Y + \frac{1}{3}C_{\rm B-L}, \mu_d = -\frac{1}{3}C_Y + \frac{1}{3}C_{\rm B-L}$$

- Also, total EM charge must vanish -> one free par'm, useful to use B=net Baryon number

$$C_{\rm B-L} = \frac{11}{28}B$$

$$\mu_X = 2C_{\rm B-L} = \frac{11}{14}B$$

Time-independent: $\frac{n_{\rm DM}}{n_{\rm B}} = \frac{2\mu_X}{B}$

- mass prediction: $m_{\rm DM} = m_p \frac{n_B}{n_{\rm DM}} \frac{\Omega_{\rm DM}}{\Omega_b} = 3{\rm GeV}$

DM mass

- Easy now to read off more general case

$$m_{\rm DM} \approx \begin{array}{cr} 6.3|L_{\rm DM}^{-1}|{\rm GeV} & \text{boson} \\ 13|L_{\rm DM}^{-1}|{\rm GeV} & \text{fermion} \end{array}$$

$$\frac{1}{4} \lesssim L_{\rm DM} \lesssim 4 \Rightarrow 1{\rm GeV} \lesssim m_{\rm DM} \lesssim 50{\rm GeV}$$

Neutrino Portal HL

other portals:
$|H|^2, F_{\mu\nu}, ..$
LLE^c

DM

X

$\bar{\nu}$

- HL is lowest-dim'l leptonic gauge-invariant in SM,-> most ops you write down for transferring asym will have HL

(Falkowski,Juknevich,Shelton)

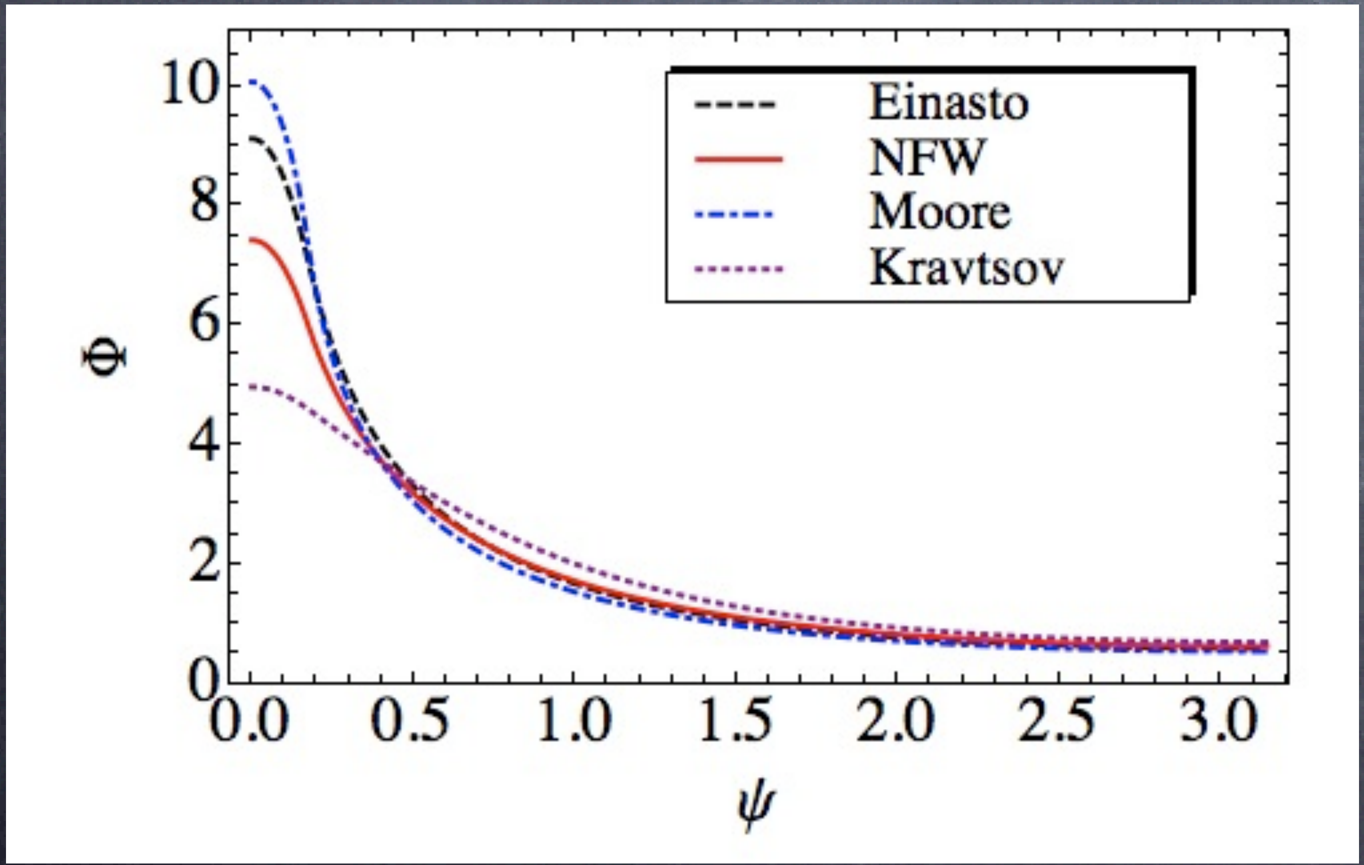
- Below mh, mW, -> $HL \sim v\nu$
- ADM quite frequently has leading signal in $\bar{\nu}$ decays!
- Plus, no anti-DM particles today-> $X \longrightarrow \bar{\nu}\bar{\nu}$

Flux from halo decays

$$\frac{d\Phi}{dE} = \frac{\Gamma}{4\pi m}\frac{dN}{dE}\int \rho_{\rm DM}(\vec{l})dl$$

	$\mathcal{J}_{\theta=10^\circ}(1)$	$\mathcal{J}_{\theta=30^\circ}(1)$	$\mathcal{J}_{\theta=180^\circ}(1)$
Einasto	12.6	6.7	1.8
Moore	13.9	6.5	1.8
NFW	10.2	6.0	1.9
Kravtsov	6.8	5.5	2.1

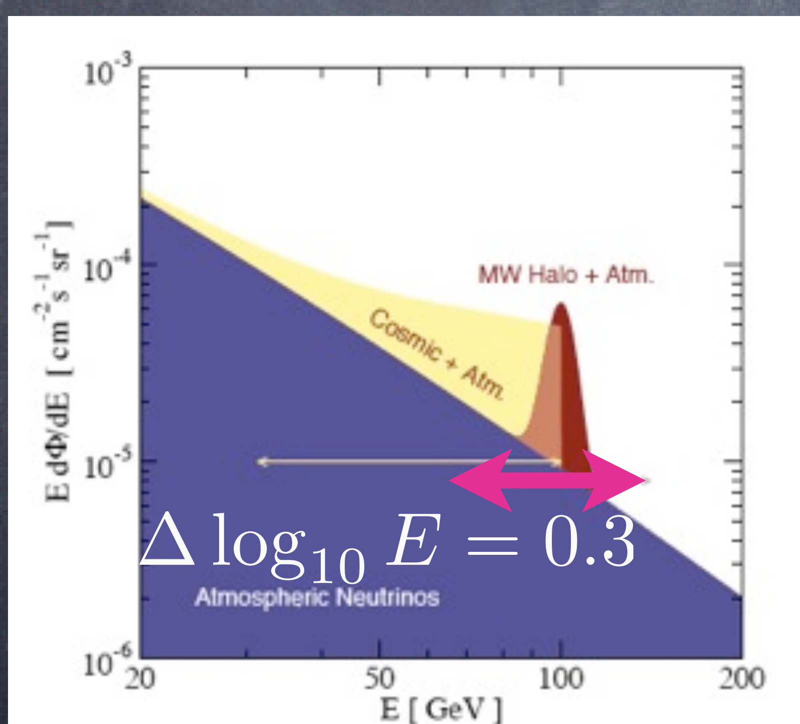
- Peaked toward galactic center, not very halo-dependant



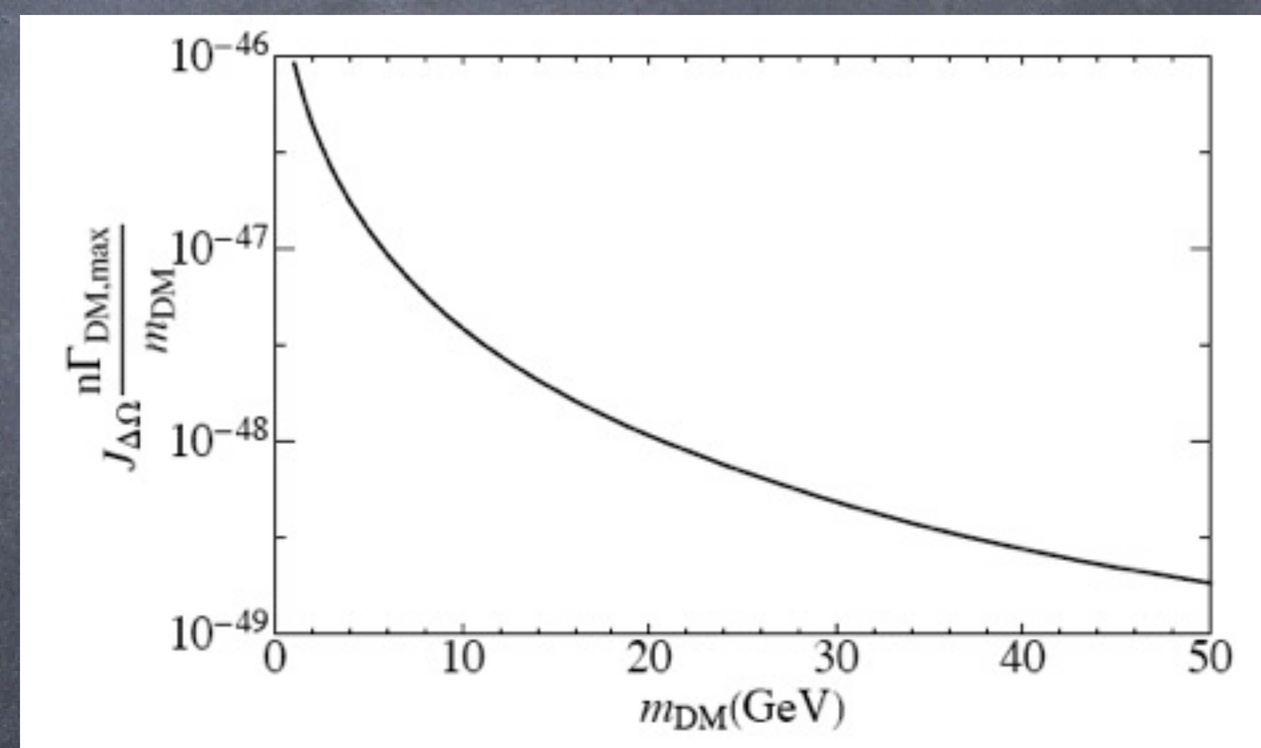
- Cosmic decays < 10% $\mathcal{J}_{\theta=180^\circ}$

Constraint

- Super-K hasn't looked for ν s from DM at $\lesssim 20\mathrm{GeV}$, doing analysis now
- Would have noticed if signal too big, say signal>background from atmospheric ν s



(from Beacom et al.)



$(t_{\mathrm{universe}}^{-1} = 1.5 \times 10^{-42} \mathrm{GeV})$

- Downside: need some luck

$$\mathcal{O}_{2\nu} = \frac{1}{2}\frac{X(HL)^2}{\Lambda^2}$$

If Λ is too large, won't see anything

$$\Lambda_{\rm min} = 6 \times 10^{13}\,\mathrm{GeV}$$

- Some hope: Already sensitive to near-GUT suppression...

- Also, freeze-out temperature must be below reheating temperature $\left(\frac{\Lambda^4}{m_{\rm pl}}\right)^{1/3} \sim T_{\rm freeze-out} < T_{\rm reheat}$

- If $T_{\rm reheat} < M_{\rm GUT}$, then $\Lambda \lesssim 5 \times 10^{16}\,\mathrm{GeV}$

(extra assumption here: $\mathcal{O}_{2\nu}$ still valid description of asym x-ter at high T)

νs vs. $\bar{\nu}$s

- After an experiment sees a bump, look at ν vs $\bar{\nu}$ composition
- Water Cherenkov detectors (Super-K) : requires more statistics than initial discovery of bump...
- Bin events into many classes, look for deviations from expected neutrino vs. anti-neutrino rates from atm background
- Example: look for extra muon in final state, expect about 10 times as many neutrinos as anti-neutrinos

$$
\begin{aligned}
\nu_e + P &\rightarrow P + e^- + \pi^+ \quad (\pi^+ \rightarrow \mu^+ + \nu_\mu) \\
\nu_e + N &\rightarrow N + e^- + \pi^+ \quad (\pi^+ \rightarrow \mu^+ + \nu_\mu) \\
\bar{\nu}_e + P &\rightarrow P + e^+ + \pi_- \\
\bar{\nu}_e + N &\rightarrow N + e^+ + \pi_-
\end{aligned}
$$

π^- gets absorbed by P

- MINOS: magnetic field-> easily distinguish charge of muon

Other operators

$$
\begin{aligned}
d=4 \quad &: \quad \mathcal{O}_1 = \psi H L \\
d=5 \quad &: \quad \mathcal{O}_2 = X \psi H L \\
d=6 \quad &: \quad \mathcal{O}_3 = \psi L L E^c \\
&\quad\;\; \mathcal{O}_4 = \psi L Q D^c \\
&\quad\;\; \mathcal{O}_5 = \psi U^c D^c D^c \\
&\quad\;\; \mathcal{O}_6 = X_1 X_2 \psi H L \\
&\quad\;\; \mathcal{O}_{2\nu} = \frac{1}{2} X (HL)^2
\end{aligned}
$$

DS particles: X boson, ψ fermion

$\Delta\mathcal{L}$	Decay	$\Gamma_{DM}\frac{dN}{dE_\nu}$	$\Lambda_{\rm min}$ (GeV)
$\mathcal{O}_2/\Lambda$	$X \to \bar{\psi}\bar{\nu}$	$\frac{m}{(3)(32\pi)}\frac{v^2}{\Lambda^2}\delta(E_\nu - m/2)$	8×10^{24}
$\mathcal{O}_{2\nu}/\Lambda^2$	$X \to \bar{\nu}\bar{\nu}$	$\frac{m}{(3)(8\pi)}\frac{v^4}{\Lambda^4}\delta(E_\nu - m/2)$	6×10^{13}
$\mathcal{O}_6/\Lambda^2$	$X_1 \to X_2^*\bar{\psi}\bar{\nu}$	$\frac{v^2}{(3)(4\pi)^3\Lambda^4}E_\nu^2\Theta\left(\frac{m}{2} - E_\nu\right)$	10^{12}
$\mathcal{O}_6/\Lambda^2$	$\psi \to X_1^* X_2^* \bar{\nu}$	$\frac{v^2}{(3)(4\pi)^3\Lambda^4}E_\nu^2\Theta\left(\frac{m}{2} - E_\nu\right)$	10^{12}
$\frac{g(\psi HL)(\chi\chi^c)}{\Lambda m_X^2}$	$\psi \to \bar{\chi}\bar{\chi}^c\bar{\nu}$	$\frac{2g^2v^2m}{(3)(4\pi)^3\Lambda^2 m_X^4}E_\nu^2(\frac{m}{2} - E_\nu)\Theta\left(\frac{m}{2} - E_\nu\right)$	$1.4g\left(\frac{10\text{GeV}}{m_X}\right)^2 10^{22}$

Trivial Observation #1

$$
\begin{aligned}
d=4 \quad &: \quad \mathcal{O}_1 = \psi H L \\
d=5 \quad &: \quad \mathcal{O}_2 = X\psi H L \\
d=6 \quad &: \quad \mathcal{O}_3 = \psi L L E^c \\
&\quad\;\; \mathcal{O}_4 = \psi L Q D^c \\
&\quad\;\; \mathcal{O}_5 = \psi U^c D^c D^c \\
&\quad\;\; \mathcal{O}_6 = X_1 X_2 \psi H L \\
&\quad\;\; \mathcal{O}_{2\nu} = \frac{1}{2} X (HL)^2
\end{aligned}
$$

DS particles: X boson, ψ fermion

$\Delta\mathcal{L}$	Decay	$\Gamma_{DM}\frac{dN}{dE_\nu}$	$\Lambda_{\rm min}$ (GeV)
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$\mathcal{O}_{2\nu}/\Lambda^2$	$X \to \bar\nu\bar\nu$	$\frac{m}{(3)(8\pi)}\frac{v^4}{\Lambda^4}\delta(E_\nu - m/2)$	6×10^{13}
$\mathcal{O}_6/\Lambda^2$	$X_1 \to X_2^*\bar\psi\bar\nu$	$\frac{v^2}{(3)(4\pi)^3\Lambda^4}E_\nu^2\Theta\left(\frac{m}{2}-E_\nu\right)$	10^{12}
$\mathcal{O}_6/\Lambda^2$	$\psi \to X_1^* X_2^*\bar\nu$	$\frac{v^2}{(3)(4\pi)^3\Lambda^4}E_\nu^2\Theta\left(\frac{m}{2}-E_\nu\right)$	10^{12}
$\frac{g(\psi HL)(\chi\chi^c)}{\Lambda m_X^2}$	$\psi \to \bar\chi\bar\chi^c\bar\nu$	$\frac{2g^2v^2m}{(3)(4\pi)^3\Lambda^2 m_X^4}E_\nu^2(\frac{m}{2}-E_\nu)\Theta\left(\frac{m}{2}-E_\nu\right)$	$1.4g\left(\frac{10\text{GeV}}{m_X}\right)^2 10^{22}$

Decay to baryons, charged leptons; not neutrinos

All have DM with (B-L)[ψ]=1

Trivial Observation #2

$$d = 4 \quad : \quad \mathcal{O}_1 = \psi H L$$
$$d = 5 \quad : \quad \mathcal{O}_2 = X \psi H L$$
$$d = 6 \quad : \quad \mathcal{O}_3 = \psi L L E^c$$
$$\mathcal{O}_4 = \psi L Q D^c$$
$$\mathcal{O}_5 = \psi U^c D^c D^c$$
$$\mathcal{O}_6 = X_1 X_2 \psi H L$$
$$\mathcal{O}_{2\nu} = \frac{1}{2} X (HL)^2$$

DS particles: X boson, ψ fermion

$\Delta\mathcal{L}$	Decay	$\Gamma_{DM} \frac{dN}{dE_\nu}$	$\Lambda_{\rm min}$ (GeV)
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$\mathcal{O}_{2\nu}/\Lambda^2$	$X \to \bar{\nu}\bar{\nu}$	$\frac{m}{(3)(8\pi)} \frac{v^4}{\Lambda^4} \delta(E_\nu - m/2)$	6×10^{13}
$\mathcal{O}_6/\Lambda^2$	$X_1 \to X_2^* \bar{\psi}\bar{\nu}$	$\frac{v^2}{(3)(4\pi)^3 \Lambda^4} E_\nu^2 \Theta\left(\frac{m}{2} - E_\nu\right)$	10^{12}
$\mathcal{O}_6/\Lambda^2$	$\psi \to X_1^* X_2^* \bar{\nu}$	$\frac{v^2}{(3)(4\pi)^3 \Lambda^4} E_\nu^2 \Theta\left(\frac{m}{2} - E_\nu\right)$	10^{12}
$\frac{g(\psi HL)(\chi\chi^c)}{\Lambda m_X^2}$	$\psi \to \bar{\chi}\bar{\chi}^c\bar{\nu}$	$\frac{2g^2 v^2 m}{(3)(4\pi)^3 \Lambda^2 m_X^4} E_\nu^2 (\frac{m}{2} - E_\nu) \Theta\left(\frac{m}{2} - E_\nu\right)$	$1.4 g \left(\frac{10\text{GeV}}{m_X}\right)^2 10^{22}$

Decay to neutrinos, + DS states

Spectrum usually sharp, from kinematics

Trivial Observation #3

$$d = 4 \quad : \quad \mathcal{O}_1 = \psi H L$$
$$d = 5 \quad : \quad \boxed{\mathcal{O}_2 = X \psi H L}$$
$$d = 6 \quad : \quad \mathcal{O}_3 = \psi L L E^c$$
$$\mathcal{O}_4 = \psi L Q D^c$$
$$\mathcal{O}_5 = \psi U^c D^c D^c$$
$$\mathcal{O}_6 = X_1 X_2 \psi H L$$
$$\mathcal{O}_{2\nu} = \frac{1}{2} X (HL)^2$$

DS particles: X boson, ψ fermion

$\Delta\mathcal{L}$	Decay	$\Gamma_{DM}\frac{dN}{dE_\nu}$	$\Lambda_{\rm min}$ (GeV)
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$$L(X) + L(\psi) = -1$$

$$L(X) \begin{matrix} > \\ < \end{matrix} 0, \quad \begin{matrix} X^* \\ X \end{matrix} \ \text{DM}$$

Trivial Observation #4

$$d = 4 \quad : \quad \mathcal{O}_1 = \psi H L$$
$$d = 5 \quad : \quad \mathcal{O}_2 = X \psi H L$$
$$d = 6 \quad : \quad \mathcal{O}_3 = \psi L L E^c$$
$$\mathcal{O}_4 = \psi L Q D^c$$
$$\mathcal{O}_5 = \psi U^c D^c D^c$$
$$\mathcal{O}_6 = X_1 X_2 \psi H L$$
$$\mathcal{O}_{2\nu} = \frac{1}{2} X (HL)^2$$

DS particles: X boson, ψ fermion

$\Delta\mathcal{L}$	Decay	$\Gamma_{DM} \frac{dN}{dE_\nu}$	$\Lambda_{\min}$ (GeV)
$\mathcal{O}_2/\Lambda$	$X \to \bar{\psi}\bar{\nu}$	$\frac{m}{(3)(32\pi)} \frac{v^2}{\Lambda^2} \delta(E_\nu - m/2)$	8×10^{24}
$\mathcal{O}_{2\nu}/\Lambda^2$	$X \to \bar{\nu}\bar{\nu}$	$\frac{m}{(3)(8\pi)} \frac{v^4}{\Lambda^4} \delta(E_\nu - m/2)$	6×10^{13}
$\mathcal{O}_6/\Lambda^2$	$X_1 \to X_2^* \bar{\psi}\bar{\nu}$	$\frac{v^2}{(3)(4\pi)^3 \Lambda^4} E_\nu^2 \Theta\left(\frac{m}{2} - E_\nu\right)$	10^{12}
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d=6: Λ a little below M_{GUT}

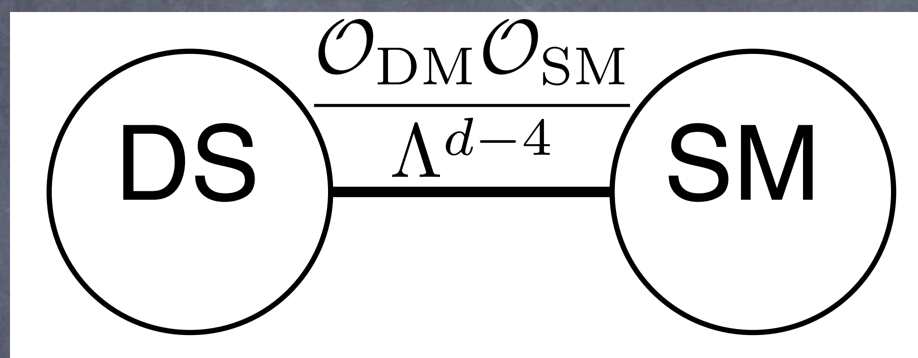
d=5: Λ >> M_{GUT} .

Lepton # and DM lifetime

- $U(1)_L$ at high T becomes $U(1)_L \times U(1)_{\mathrm{DM}}$

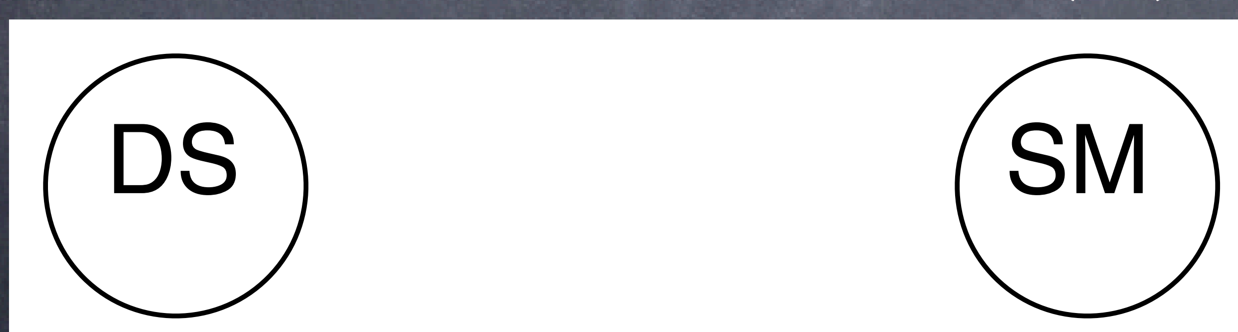
$U(1)_L$

UV



$U(1)_{\mathrm{DM}}$ $U(1)_L$

IR



e.g $X\psi H L$

$$L(X) = -\frac{1}{3} \quad L(\psi) = -\frac{2}{3}$$

~~$X \to \psi + \text{DS states}$~~

Other model-building stuff

- See-saw mechanism
- Lepton number protects DM lifetime, so violating lepton number with heavy right-handed neutrino masses is potentially dangerous $\langle\phi\rangle NN$ $L(\phi) = -2$
- $X\psi HL$ is nice in this respect - easily UV-completed to model with accidental lepton number in DS: new d,d^c doublet fields with Y= ±1/2

$$\Delta\mathcal{L} = \lambda\psi dH + \lambda' L d^c X + m_d d d^c$$

- No DS allowed renormalizable couplings to Lepton-breaking $\langle\phi\rangle$

Other model-building stuff

- suppressing psi X H L
- Spont. broken U(1):

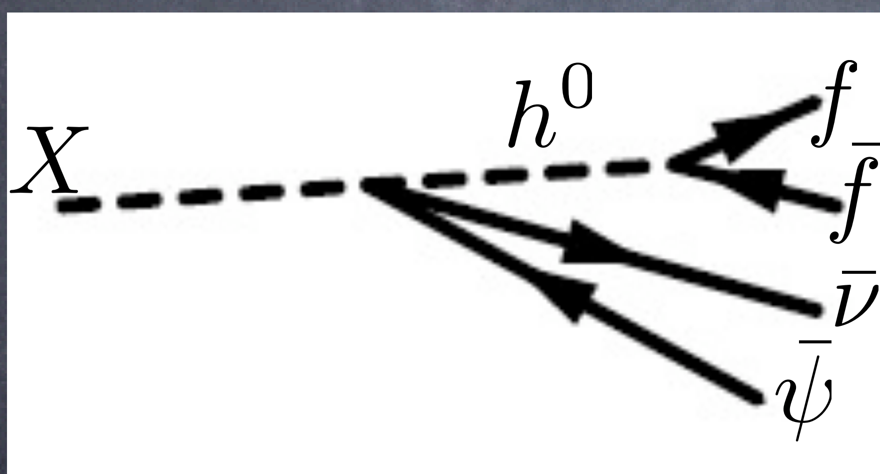
	$U(1)$
X, d_2	1
S, d_2^c	-1
else	0

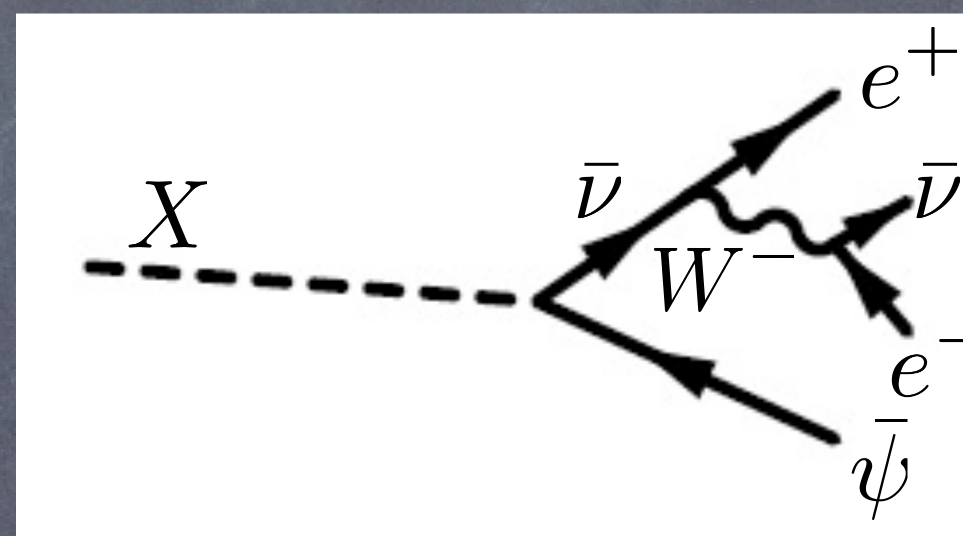
$$\Delta\mathcal{L} = \lambda\psi d_1 H + \lambda' L d_2^c X + m_{d,i} d_i d_i^c + cS d_2 d_1^c$$

$$\rightarrow \frac{c\lambda\lambda'\langle S\rangle}{m_d^2} X\psi H L$$

Other decays

- Can always produced charged SM states, but must go through off-shell H,W, or Z





- $v^2 \to m_{\rm DM}^2$
  g^4, m_W^{-4}
- phase space factors

Very suppressed Br fraction:

$$\gamma_{e^+} \sim \frac{g^4}{(2\pi)^4}\frac{m_{\rm DM}^4}{m_W^4} \sim 10^{-9}\left(\frac{m_{\rm DM}}{10{\rm GeV}}\right)^4$$

E.g. Positron flux limits

- Abundance set by balance between production and depletion

$$Q_{e^+}(E) \approx \frac{d}{dE}\left(\frac{dE}{dt} n_{e^+}(E)\right) + \frac{n_{e^+}}{T} \approx \frac{n_{e^+}}{T}$$

- T = diffusion time

$$r = \sqrt{D \times t}, \quad D = 3 \times 10^{28} \mathrm{cm}^2/\mathrm{s}, \longrightarrow T \approx 10^6 \mathrm{yr}$$

$$\text{Galactic height } h \approx 10^3 ly$$

- neutrinos just travel straight through galaxy

$$n_\nu \sim \frac{\rho_{\mathrm{DM}} \Gamma_{\mathrm{DM}}}{m_{\mathrm{DM}}} R_G, \quad n_{e^+} \sim \gamma_{e^+} \frac{\rho_{\mathrm{DM}} \Gamma_{\mathrm{DM}}}{m_{\mathrm{DM}}} T \sim (10\gamma_{e^+}) n_\nu$$

Neutrinos are leading signature, even with ~1000 times neutrino bkgd

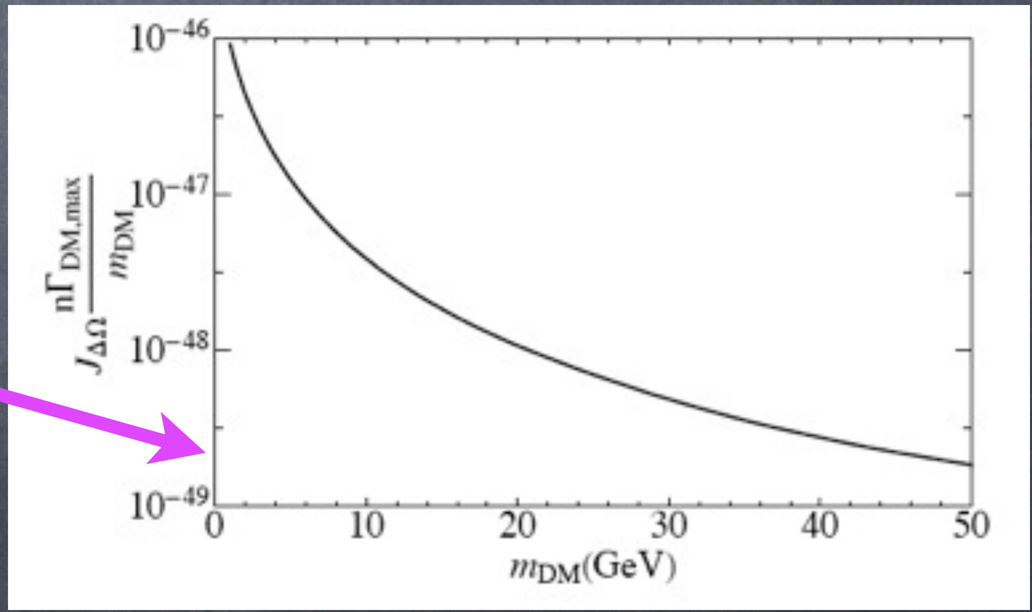
Annihilations

- No signal from annihilations in halo, because of freeze-out bound: asymmetry transfer must freeze out above the mass of the DM particle

$$\sigma_m m_{\rm DM}^3 \lesssim H(m_{\rm DM})$$

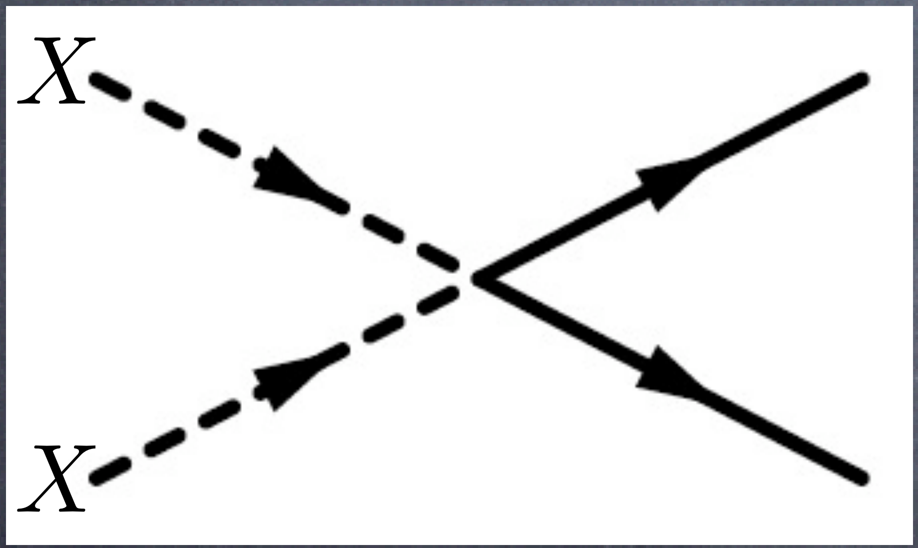
$$\frac{\Gamma_0}{m_{\rm DM}} \lesssim \frac{\sigma_0}{\sigma_m} 10^{-61} \left(\frac{1\rm GeV}{m_{\rm DM}}\right)^3$$

Would need huge enhancement of σ_0 over σ_m

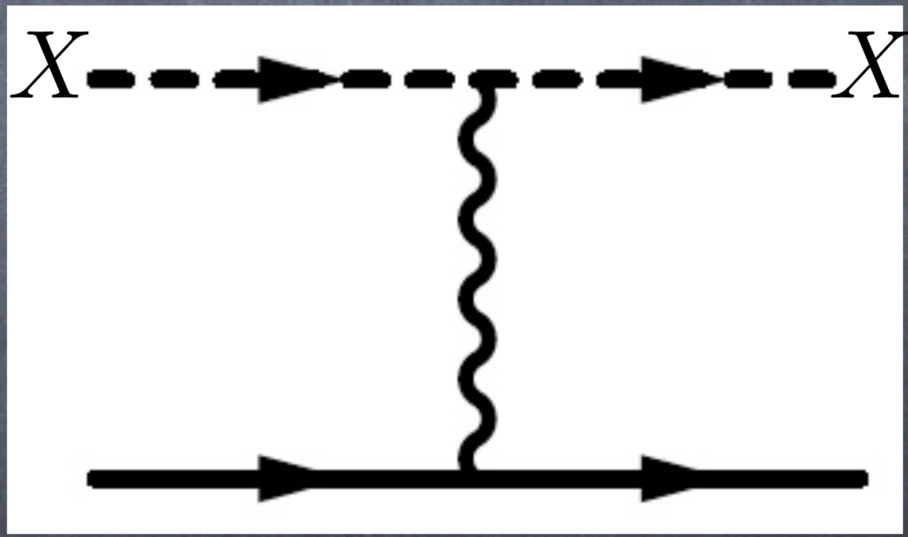


Annihilations in Sun

- Small annihilation rate can be accommodated by large scattering cross-section
- In ADM, scattering and annihilation x-sec can be totally different!



vs.

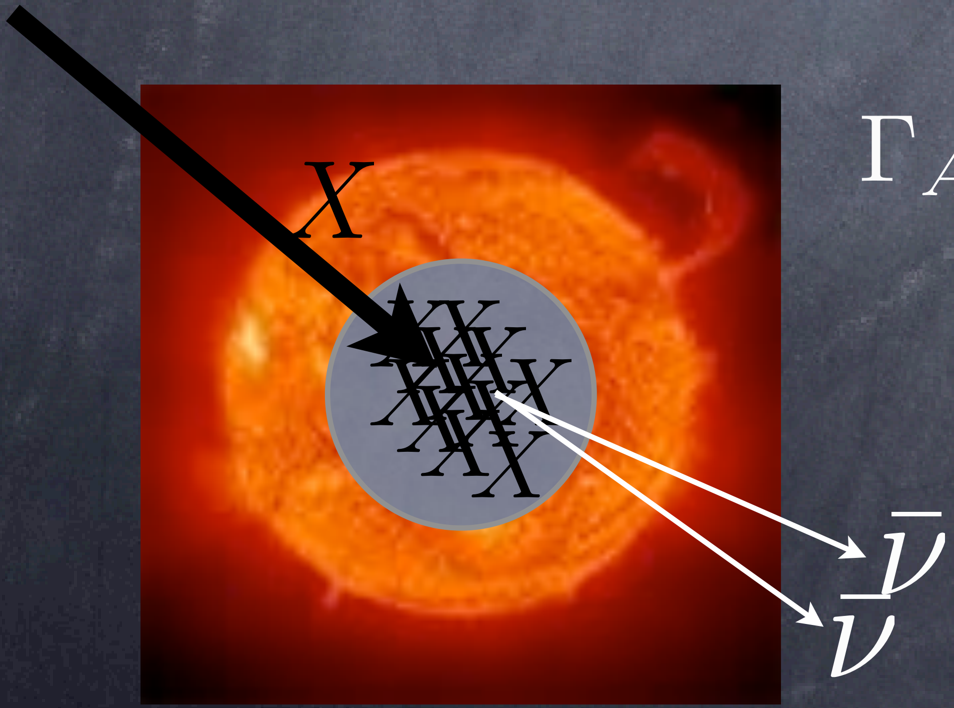


Annihilations in Sun

- Atmospheric background to overcome at 5GeV w/i 10 deg around sun: $0.4\mathrm{m}^{-2}\mathrm{s}^{-1}$
- Need annihilation rate $\Gamma_A > 1.1 \times 10^{23}\mathrm{s}^{-1}$

$$\dot{N} = C - AN^2$$

- For $t < \tau_{\mathrm{eq}} = 1/\sqrt{CA}$, rate grows like t²:



$$\Gamma_A = \frac{1}{2}AN^2 = \frac{1}{2}C^2At^2$$

Annihilations in Sun

- DM trapped in sun thermalizes, thermal radius

$$r_{\rm th} = 0.045 R_\odot \left(\frac{5\mathrm{GeV}}{m_{\rm DM}}\right)^{\frac{1}{2}} \qquad A = \frac{\langle \sigma_A v\rangle}{V_{\rm eff}}$$

$$\frac{1}{2} C^2 A t_\odot^2 \lesssim 10^{23}\mathrm{s}^{-1} \left(\frac{C}{10^{27}\mathrm{s}^{-1}}\right)^2 \left(\frac{\langle \sigma_A v\rangle_{T_\odot}}{\langle \sigma_A v\rangle_m}\right)^{\frac{1}{2}} \left(\frac{m_{\rm DM}}{5\mathrm{GeV}}\right)^{\frac{1}{2}} \left(\frac{g_*}{60}\right)^{\frac{1}{2}}$$

$$t_\odot \ll \tau_{\rm eq}$$

$$C \approx 10^{27}\mathrm{s}^{-1} \left(\frac{\sigma_S}{0.05\mathrm{pb}}\right)\left(\frac{5\mathrm{GeV}}{m_{\rm DM}}\right)$$

(Gould, Press, Spergel)

- Ruled out by direct detection: $\sigma_S \lesssim 3 \times 10^{-4}\mathrm{pb}$

from DAMA at m=5 GeV

Enhancement from WIMP-WIMP scattering

$$\dot{N} = C + C_X N - AN^2$$

$$N(t_\odot) = Ct_\odot \left(\frac{\exp(C_X t_\odot) - 1}{C_X t_\odot} \right)$$

$$C_{\rm Eff} = C \frac{e^{C_X t_\odot} - 1}{C_X t_\odot}$$

- Need enhancement of 170

(A. Zentner)

Need $C_X t_\odot$ = 7.1

Classical Sommerfeld Enhancement

$$C_X = \sqrt{\frac{3}{2}} n_{\rm DM} \sigma_S \bar{v} \left(\frac{v_{\rm esc}(R_\odot)}{\bar{v}} \right)^2 \left\langle \frac{v_{\rm esc}^2(r)}{v_{\rm esc}^2(R)} \right\rangle \frac{{\rm erf}(\eta)}{\eta}$$

$$\eta = \sqrt{\frac{3}{2}} \frac{v_\odot}{\bar{v}}$$

Enhancement from WIMP-WIMP scattering

- Geometric Cross-section:

$$C \lesssim \pi r_{\rm th}^2 n_{\rm DM} \bar{v} \left(\frac{v_{\rm esc}}{\bar{v}}\right)^2 \approx 2 \times 10^{27} {\rm s}^{-1} \left(\frac{5{\rm GeV}}{m_{\rm DM}}\right)$$

- Bounds: Ellipsoidal dwarf galaxies

$$s_X \equiv \frac{\sigma_S}{m_X} < 2 \times 10^{-25} {\rm cm}^2/{\rm GeV}$$

$$\searrow \quad C_X t_\odot < 8.3 \frac{\rho_{\rm DM}}{0.4{\rm GeV}/{\rm cm}^3}$$

- Looks like a signal is possible

- Obviously, very sensitive to O(1) effects...

The End!

Summary

Other model-building stuff

- getting low mass
-

νs vs. $\bar{\nu}$s

- MINOS: magnetic field-> easily distinguish charge of muon